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Portable Probes to Measure Electrical Conductivity and Soil Quality in the Field

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Abstract: Soil electrical conductivity (EC) is a useful indicator in managing agricultural systems, but tools for convenient and inexpensive measurements in the field are generally lacking. Handheld conductivity probes were designed to evaluate in-field naturally occurring and human-induced total soluble electrolyte levels in soil and water. The probes were used to survey and monitor EC in the field and to assess soil and water quality as related to environmental stability and sustainable food production. A pencil-sized 16-cm probe (PP) was connected to a handheld Hanna (DiST WP 4) conductivity meter, resulting in an economical, compact, and easy to use device. The tool provided accurate and precise results compared with laboratory instrumentation under standardized conditions of soil water content and temperature. Soil samples, varying widely in texture and organic matter content, and having ECs ranging from 0.13 to 2.32 $dS\,m^{-1}$ were used for comparison. Mean values and coefficients of variation were similar for the PP and the commercial laboratory EC meter with values determined with the two instruments being strongly correlated ($r^2 = 0.96$–0.99). The handheld and PP probes effectively replaced expensive and cumbersome laboratory and field instruments used to measure EC in water and soil samples. The

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probe measurements were useful alternatives to conventional methods as they enabled accurate and precise measurement of EC, were a manageable size for field use, and were reliable and economic. The utility of EC as an indicator of soil health, plant-available N, and environmental quality is also presented.

Keywords: Please supply

INTRODUCTION

Agriculture is challenged to produce sufficient food yet conserve the quality of essential soil, water, and air resources. Strategies for sustainable management include conservation of soil organic matter, minimizing soil erosion, balancing nutrients for environmental and production needs, and better use of renewable resources (Doran 2005). The utility of soil and water electrical conductivity (EC) as indicators of condition and stewardship of farmlands and water resources (Patni et al. 1998; The H. John Heinz III Center for Science 2002) has created need for conductivity probes that can rapidly estimate EC in the field. Field salinity measurements using EC have evolved over the past 30 years from four-electrode techniques using probes connected to generators and meters that require contact with the soil to electromagnetic methods that do not require soil contact. Theories of these measurement techniques have been developed and verified for their accuracy (Rhoades and Corwin 1981).

Soil EC is an easily measured yet reliable indicator of soil quality, crop performance, nutrient cycling, and biological activity and can serve as a quick indicator of plant-available nitrate-N (Doran 2005; Patni et al. 1998; Johnson et al. 2005; Eigenberg et al. 2000; Patriquin et al. 1993; Smith and Doran 1996). Comparison studies of EC measurements using soil-saturated pastes (EC_e) vs. 1 : 1 soil water extractions ($EC_{1:1}$) provide threshold values for in-field evaluation of plant tolerance to soil EC (Smith and Doran 1996). In general, an EC range of $0-1\ \mathrm{dS\ m^{-1}}$ indicates good soil health. Conductivity values above $1-2\ \mathrm{dS\ m^{-1}}$ result in reduced growth of salt-sensitive plants and disruption of the microbial mediated processes of nitrification and denitrification (Doran 2005; Smith and Doran 1996).

Another emerging use of EC is for estimation of nitrate concentration, because the two measurements are positively correlated in many agroecosystems (Patriquin et al. 1993; Smith and Doran 1996; Nissen et al. 1998). Therefore, soil EC is a useful measurement in any study involving varying levels of N fertilizer application. Smith and Doran (1996) found that soil EC could be used to estimate soil nitrate-N levels in low lime soils (pH < 7.2) where:

$$140 \times (\mathrm{EC} - \mathrm{background},\ \mathrm{dS\ m^{-1}}) = \mathrm{ppm\ Nitrate\text{-}N}$$

The background EC of a given soil is determined by subtracting the EC equivalence of the analyzed nitrate-N content of the soil (EC_{back} = ppm Nitrate-N/140) from the overall measured EC.

An estimate of soil nitrate can be very useful for a late spring test for N sufficiency for nonlimited yield of corn (*Zea mays* L.) (Adviento et al. 2004). For this test, soil is generally sampled to a depth of 30 cm when corn plants are in the 4–6 leaf stage or about 15–30 cm tall. At this stage, a nitrate-N concentration of 25 ppm is sufficient for optimal yield of fertilized corn, which is equivalent to a soil EC of about 0.18 dS m^{-1} in low lime soils (Doran 2005; Adviento et al. 2004). For corn receiving manure or in corn after alfalfa, the critical value is 16 ppm nitrate-N or about 0.11 dS m^{-1} soil EC. Conductivity can also serve as an indicator of nitrate-N loss after a heavy rain as a soil EC of 0.01 dS m^{-1} indicates less than 1.4 ppm nitrate-N.

Soil EC can also be used as a sensitive indicator of microbially mediated processes of N transformations and the production of greenhouse gases. A soil EC value above 1 dS m^{-1} can result in increased loss of fertilizer and available N as the potent greenhouse gas nitrous oxide (Doran 2005; Smith and Doran 1996; Adviento et al. 2004). Increased greenhouse gas emissions can negate remediation of global warming, which is offset by increased carbon dioxide tie-up in soil organic matter with reduced tillage management. Nitrous oxide is about 300 times more effective than carbon dioxide in radiative warming of the atmosphere. Nitrous oxide production from nitrification, an aerobic process, is inhibited by soil EC values greater than 1 dS m^{-1} but production from denitrification, an anaerobic process, is increased by soil EC values above 0.8 dS m^{-1} (Smith and Doran 1996; Adviento et al. 2004; Arnos et al. 2005).

A primary objective of this research was to describe the design and application of the PP when attached to a Hanna EC meter and to compare its precision and accuracy with a laboratory bench-top conductivity meter. A secondary objective of this research was to describe two precursor probe designs of the PP, their application, and usage in the field. The data presented demonstrate the utility of handheld conductivity probes for rapidly estimating soil EC in the field and their use in determining late spring fertilizer needs in corn and soil quality as related to the activity of plants and microorganisms, N cycling, and greenhouse gas emissions.

MATERIALS AND METHODS

Probe Development and Construction

Three probes (Figure 1) designed for measuring soil and water EC in the field and laboratory were constructed and tested at the USDA-ARS Soil and Water Conservation Research Unit in Lincoln, Nebraska.

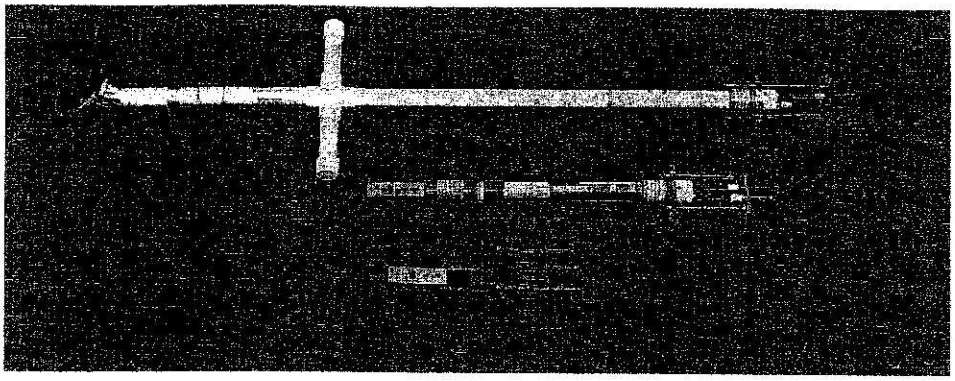


Figure 1. Handheld field and laboratory probes developed by the USDA/ARS/SWCRU for rapid in-field and laboratory analysis of soil electrical conductivity.

The Bad Boy II (BBII) 75-cm probe design (Figure 2) consisted of two metal rods 5-mm diameter by 18-cm long attached through a 3 1/2-cm i.d. PVC pipe cap, placed on a 3 1/2-cm o.d. PVC pipe (electrical conduit) with an overall length of 75 cm. Insulated wires ran from the metal rods (electrodes), through the conduit to the Hanna (DiST WP 4) conductivity meter. The pointed metal rods (coated with epoxy, except for 10 mm on the end of each probe) were inserted through a spring-loaded Plexiglas® base plate that maintained a spacing of 2 1/2 cm at the soil surface as the metal rods were inserted into the soil. A 470-ohm resistor placed across the electrodes inside the plastic conduit is attached to an exterior switch. When the switch is ON, current passes through the resistor and back to the meter. A curve was developed by calibrating the meter with a standard solution of 0.01 *M* KCl (1.41 dS m^{-1}) at three different temperatures (40°C, 20°C, and 5°C) with the resistor switch in the OFF position. The resistor switch, at each

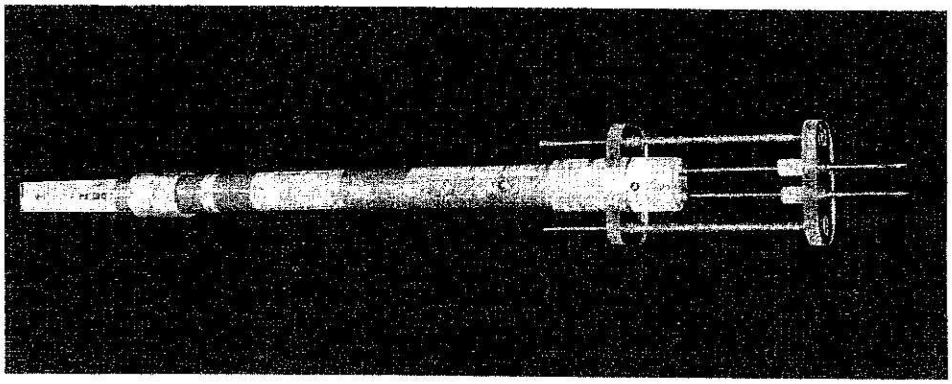


Figure 2. Handheld field probe (Bad Boy II) developed by the USDA/ARS/SWCRU for rapid in-field calibration and analysis of soil electrical conductivity (overall length 75 cm).

temperature, was then placed in the ON position, and a meter reading was recorded. A regression curve was developed and used to correct for soil temperature differences when calibrating the probe in the field, without using a standard calibration solution.

The Bad Boy III (BBIII) 150-cm probe was the second probe design (Figure 3) constructed with a T-handle and an overall length of 150 cm, which allowed the operator to take readings while standing upright. The BBIII was constructed similarly to the BBII but did not have a resistor switch for temperature correction.

The PP design (Figure 4) is 16-cm long as illustrated in Figure 5. It consists of a 1.59-mm diameter × 120-mm-long brass rod insulated with heat shrink tubing (primary probe) inserted inside a 3.19-mm i.d. × 110-mm-long brass tube (secondary probe). Two insulated wires are soldered to the ends of each probe and likewise attached to Molex sockets that are inserted into a connector (Tooling done by Zermatt Tool, Adams, NE 68301) designed to plug into the Hanna (DiST WP 4) conductivity meter. The secondary probe is insulated with heat shrink tubing and inserted into a brass tube (4.77-mm i.d. × 100-mm long) for protection. A nylon tube (5-mm i.d. × 10-mm o.d. × 50-mm long) was placed over the end of the protective cover and used as a handle. The primary probe and secondary probe tips are extended 5 mm beyond the heat shrink tubing, allowing for good soil/probe contact. The PP is inserted into a nylon sheath fitted with a pocket clip to protect the probe and operator while transporting between sampling locations.

Probe Performance and Applications

The precision and accuracy of three PPs with varying primary probe lengths (2.5, 5.0, and 10.0 mm) were also evaluated, as was a new prototype Hanna

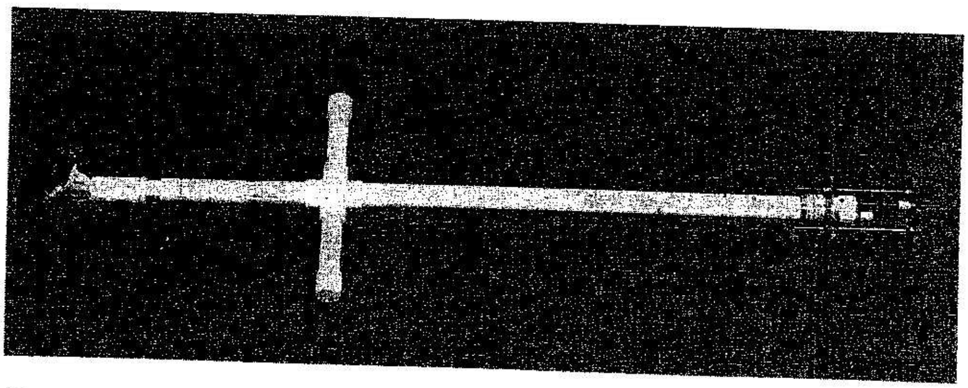


Figure 3. Handheld field probe (Bad Boy III) developed by the USDA/ARS/SWCRU for rapid in-field analysis of soil electrical conductivity (overall length 150 cm).

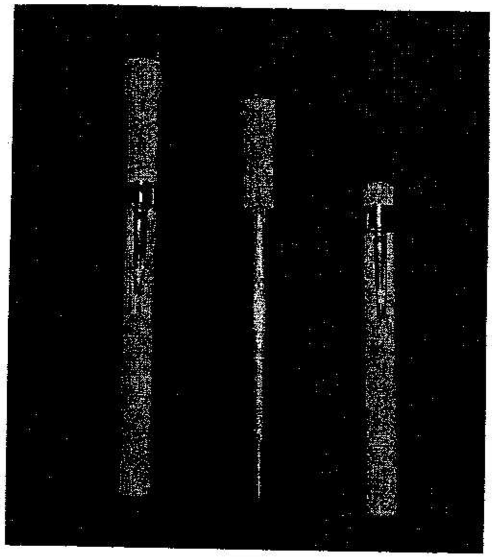
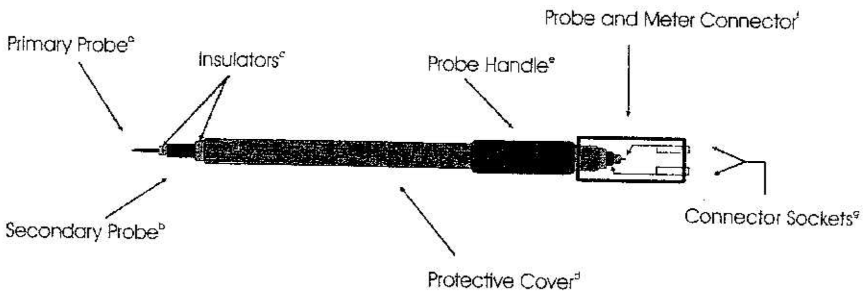


Figure 4. Pencil probe developed by the USDA/ARS/SWCRU for rapid field and laboratory analysis of electrical conductivity.

conductivity hand probe. The PPs were attached to a Hanna (DiST WP 4) conductivity meter and used to take triplicate random measurements for 9 EC water calibration standards [traceable to the National Institute of Standards and Technology (NIST)] and 19 benchmark soils of widely varying texture



[a] 1.59 mm O.D. solid brass rod 120 mm long.

[b] 3.19 mm I.D. brass tube 110 mm long.

[c] Approximately 1.59 mm I.D. and 3.19 mm I.D. heat shrink tubing respectively.

[d] 4.77 mm I.D. brass tube 100 mm long.

[e] 5 mm I.D. x 10 mm O.D. x 50 mm long nylon tube.

[f] Probe and meter connector (Zermatt Tool, Adams, NE).

[g] Connector sockets (Molex 1.57 mm female).

Figure 5. Pencil probe schematic. (Parts were glued together with epoxy.)

and soil organic matter content. Samples were analyzed in the laboratory at constant temperature (~22°C). Water and soil samples were placed in 30-mL wide-mouth plastic bottles with lids (Nalgene Company P/N 2103-0001). The PP was calibrated by using a 0.01 *M* KCl (1.41 dS m^{-1}) calibration standard (Fisher Scientific P/N 09-328-11). Twenty mL of distilled deionized water was added to 20 g of soil and shaken by hand for 1 min. Samples were equilibrated for 30 min and then shaken before EC measurements were made. After the PP was inserted to the desired depth in the container, electrical current was induced between the primary and secondary probe tips. The Hanna (DiST WP 4) conductivity meter measures the resistance and converts the reading to EC. The EC sample volume measured is elliptical and can be influenced by the bottom and sides of the bottle; therefore, the PP was positioned in the center of the container. Water and soil sample results were averaged after randomly analyzing three replicates. The PP measurements were compared with readings taken with the Hanna (DiST WP 4) conductivity meter without the PP attached and with those from a laboratory bench top Markson (Model 1062) conductivity meter and probe (P/N 625 dip cell).

The pencil probe (5-mm tip) was also used by crop consultants (Shannon Gomes and Tom Hillyer, Hillyer Agriservices, West Liberty, IA) in 2003 to measure soil EC and estimate nitrate-N contents from 136 cornfields in SW Iowa and Nebraska during the last week of April and first week of June. Eight soil samples were taken in an "X" pattern from the surface 0–30 cm at each site and composited for analysis. Soil EC was measured with the PP on a 1 : 1 soil to distilled water mixture which was shaken 25 times before analysis. Soil Nitrate-N was also run for each sample using an NO_3-specific ion electrode by an independent laboratory.

The PP (5-mm tip) was also used to assess the N status of corn plants in the field at about tasseling time. To do this, corn plants from N fertilizer treatments (adequate N vs. no N plots) were selected from irrigated corn, fertilizer, and manure management plots (Eigenberg et al. 2000) according to plant color (green or yellow). The conductivity of each corn stalk was measured by inserting the pencil probe into the center of the stalk on the 4th internode of each plant. Although nitrate-N cannot be directly estimated from EC, the difference in nitrate between the green and yellow plants can be estimated from the following:

$$\text{Nitrate-N (mg kg}^{-1}) = (\text{green plant EC} - \text{yellow plant EC}) \times 140\ (\text{mg kg}^{-1}\ \text{Nitrate-N per dS m}^{-1})$$

Confirmation of this estimate was made by cutting both plants at the point where EC was measured and exuding cell sap from the stalk with locking pliers; the sap was then analyzed for nitrate and nitrite-N using Hach Aquachek test strips.

The BBII probe was tested in a cornfield where soil temperature fluctuates, space between rows is limited, N fertilizer rates varied considerably, and accurate assessments are needed. Soil temperature was taken and the probe was calibrated by using a correction curve. In-field soil EC readings were made in July and August 2001 in plots receiving 0, 200, and 300 kg NH_4NO_3-N ha^{-1}. Soil EC was measured within gas-sampling cylinders (15-cm diameter) which each received 500 mL of distilled water to saturate the soil. Probe readings were taken at a depth of 7.5 cm 4–12 h after saturation. Two measurements were taken between crop rows, one near a subsurface drip irrigation tape and the other without, in each of four replicates, and treatment means (n = 8) were calculated for both sampling dates. Soil cores 7.5-cm deep were collected 15 cm from each ring. Soil samples were extracted by using a 1 : 1 soil water mixture and analyzed by a laboratory bench-top Markson (Model 1062) conductivity meter and probe (P/N 625 dip cell). Nitrate-N was also determined on these samples. Further details are given by Amos et al. (2005).

The BBIII probe was used in preplant corn (*Zea mays* L.) fields to locate and avoid starter-fertilizer bands (preplant injection after strip tillage) when soil sampling, to assess the depth of fertilizer injection and aid in seed placement relative to the starter fertilizer. For these applications, accurate EC measurements were not required, so the length of the handle on the probe was increased. This adaptation allowed the operator to walk through the preplant field quickly and take readings without bending over. Soil temperature correction was not necessary to find relative EC differences.

RESULTS AND DISCUSSION

The accuracy and precision of PPs attached to the Hanna (DiST WP 4) conductivity meter for measurement of EC in water and 1 : 1 soil to water compared well with the Markson (Model 1062) conductivity meter (P/N 625 dip cell), assumed to be a standard for measuring EC. All three PPs with varying primary probe lengths (2.5, 5.0, and 10.0 mm) had acceptable coefficients of variation (Tables 1 and 2) for water (range 0.7–10.1%, average = 3.4%) and soil $EC_{1:1}$ (range 0.0–25.3%, average = 9.3%) readings. Similar coefficients of variation (Tables 1 and 2) resulted when the Hanna (DiST WP 4) conductivity meter without the PP was used to measure water (range 0.0–4.5%, average = 1.6%) and soil $EC_{1:1}$ (range 1.1–24.9%, average = 9.0%) conductivities. Coefficients of variation (Tables 1 and 2) were essentially the same for the Markson (Model 1062) conductivity meter (P/N 625 dip cell) when water (range 1.0–5.8%, average = 2.2%) and soil $EC_{1:1}$ (range 0.6–23.2%, average = 9.5%) readings were compared with the PPs and the Hanna (DiST WP 4) conductivity meter.

Table 1. Comparison of certified conductivity standards using a pencil probe vs. conventional meters

	NIST traceable[a] (dS m^{-1})								
Standards	0.1[b]	0.5[c]	0.7[c]	1.0[b]	1.4[b]	2.1[c]	3.9[c]	7.0[c]	10.0[c]
2.5 mm[d]	0.13(5.8)[h]	0.56(6.7)	0.83(6.8)	1.19(1.2)	1.48(2.6)	2.20(1.6)	3.49(2.2)	4.91(2.9)	5.99(8.2)
5.0 mm[d]	0.12(10.1)	0.51(2.6)	0.75(3.0)	1.09(2.1)	1.40(3.3)	2.00(3.8)	3.52(4.1)	5.22(1.8)	6.77(.7)
10.0 mm[d]	0.13(5.8)	0.53(5.2)	0.80(0.8)	1.12(1.7)	1.50(1.8)	2.11(3.6)	3.45(.7)	5.04(1.4)	6.18(1.8)
Prototype[e]	0.11(0.0)	0.40(0.0)	0.65(0.8)	0.96(1.0)	1.35(4.5)	1.99(0.7)	3.93(1.4)	7.25(0.2)	10.19(3.1)
Hanna[f]	0.10(0.0)	0.47(4.5)	0.76(0.8)	1.10(1.2)	1.45(1.1)	2.18(1.3)	4.07(2.4)	6.97(1.6)	9.95(1.8)
Markson[g]	0.11(5.8)	0.45(4.7)	0.71(1.7)	1.01(1.5)	1.42(1.2)	2.02(2.0)	3.91(1.0)	7.01(1.0)	10.06(1.0)

[a]Values presented are the mean values for three repetitive measurements of standard solutions.
[b] Fisher conductivity standards (Potassium Chloride) certified value $\pm 0.25\%$.
[c]Myron L Company conductivity standards (Sodium Chloride) certified value $\pm 1.0\%$.
[d]Pencil probe (2.5-, 5.0-, and 10.0-mm primary probes and 5.0-mm secondary probe) attached to Hanna conductivity meter (DiST WP 4).
[e]Hanna Prototype hand pencil probe.
[f]Hanna conductivity meter (DiST WP 4).
[g]Markson conductivity meter (Model 1062) with a conductivity probe (P/N 625 dip cell).
[h]Numbers in parentheses are coefficients of variation (%).

Table 2. Electrical conductivity comparison for a 1 : 1 soil to water mixture using the pencil probe vs. Hanna and Markson conductivity meters

Benchmark soils[b] texture (% org. C)	Electrical conductiviy readings[a] ($dS\ m^{-1}$)				
	2.5 mm[c]	5.0 mm[c]	10.0 mm[c]	Hanna[d]	Markson[e]
Barnes l (2.3)	1.28 (3.2)[f]	1.25 (6.8)	1.26 (8.1)	1.27 (5.1)	1.26 (3.2)
Caribou l (2.6)	0.51 (5.0)	0.51 (5.2)	0.50 (4.7)	0.52 (6.7)	0.51 (9.9)
Cecil sl (3.1)	1.37 (0.8)	1.31 (3.5)	1.31 (2.8)	1.32 (3.1)	1.27 (2.8)
Clarion sc (1.4)	1.00 (6.8)	0.94 (3.8)	0.96 (5.9)	0.96 (6.8)	1.00 (7.0)
Crider sil (2.1)	2.32 (3.9)	2.07 (10.0)	2.16 (10.5)	2.22 (5.6)	2.14 (7.6)
Fort Collins scl (0.8)	0.84 (2.1)	0.84 (3.0)	0.85 (1.2)	0.88 (2.4)	0.82 (3.7)
Frederick sil (2.2)	1.31 (6.9)	1.29 (8.1)	1.29 (9.0)	1.32 (5.9)	1.29 (4.5)
Hord sil (1.0)	1.00 (3.5)	1.03 (2.5)	1.01 (2.5)	1.00 (4.4)	1.02 (0.6)
Houston Black sic (1.6)	1.38 (11.3)	1.34 (11.0)	1.38 (10.1)	1.42 (6.7)	1.33 (14.1)
Kole Kole l (3.5)	0.56 (1.0)	0.55 (1.0)	0.55 (0.0)	0.58 (2.6)	0.52 (1.1)
Miami sil (1.3)	1.24 (4.9)	1.19 (3.9)	1.21 (4.2)	1.21 (6.6)	1.18 (4.2)
Mohave scl (0.7)	0.80 (17.7)	0.83 (9.2)	0.81 (8.3)	0.81 (12.5)	0.81 (10.8)
Pullman sicl (1.0)	0.82 (20.5)	0.83 (18.2)	0.82 (18.6)	0.84 (18.0)	0.81 (19.3)
Rains sil (3.3)	0.69 (19.3)	0.66 (17.6)	0.66 (20.5)	0.68 (17.1)	0.65 (22.2)
Sharpsburg sicl (1.8)	1.49 (11.6)	1.44 (10.4)	1.49 (14.5)	1.45 (13.6)	1.44 (12.1)
Valentine s (0.9)	0.15 (24.7)	0.13 (20.4)	0.14 (21.4)	0.13 (20.4)	0.13 (19.9)
Wahiawa c (1.3)	0.50 (1.2)	0.51 (3.0)	0.51 (1.1)	0.54 (1.1)	0.50 (3.0)
Walla Walla sil (1.1)	0.61 (23.1)	0.62 (23.5)	0.61 (25.3)	0.60 (24.9)	0.60 (23.2)
Yolo sil (1.3)	0.68 (7.8)	0.73 (10.7)	0.73 (11.9)	0.71 (7.3)	0.68 (10.8)
Regression[g] and r^2	Y = 0.960X $r^2 = 0.986$	Y = 0.976X $r^2 = 0.994$	Y = 0.988X $r^2 = 0.995$	Y = 0.961X $r^2 = 0.961$	

[a]Values presented are the mean of three replications with 1 : 1 soil to water extracts.
[b]Benchmark samples from the continental United States and Hawaii varied in texture and % organic C; USDA/ARS/SWCRU and NRCS.
[c]Pencil probe (2.5-, 5.0-, and 10.0-mm primary probes) attached to a Hanna conductivity meter.
[d]Hanna conductivity meter (DiST WP 4).
[e]Markson conductivity meter (Model 1062) with a conductivity probe (P/N 625 dip cell).
[f]Numbers in parentheses are coefficients of variation (%).
[g]Regression and coefficient of determination (r^2) compared with Markson EC meter.

Results from the Hanna (DiST WP 4) conductivity meter and PPs were correlated with individual data points for the Markson (Model 1062) conductivity meter (P/N 625 dip cell) for both soil and water samples. The slope for all combinations had a range of 0.96–1.42, and the coefficients of determination (r^2) ranged from 0.94 to 1.00 (Figure 6, Table 2). When three of the high EC water standards, outside the normal ranges of agroecosystem samples, were removed from the analyses, the linear coefficients of determination (r^2) values ranged from 0.99 to 1.00, and the slopes ranged from 0.91 to 0.99 for a conductivity range of 0–2.5 dS m^{-1} (data not shown).

These results suggest that the pencil probes for measurement of EC can be used for quantitative a measurement within the range of 0–2.5 dS m^{-1}

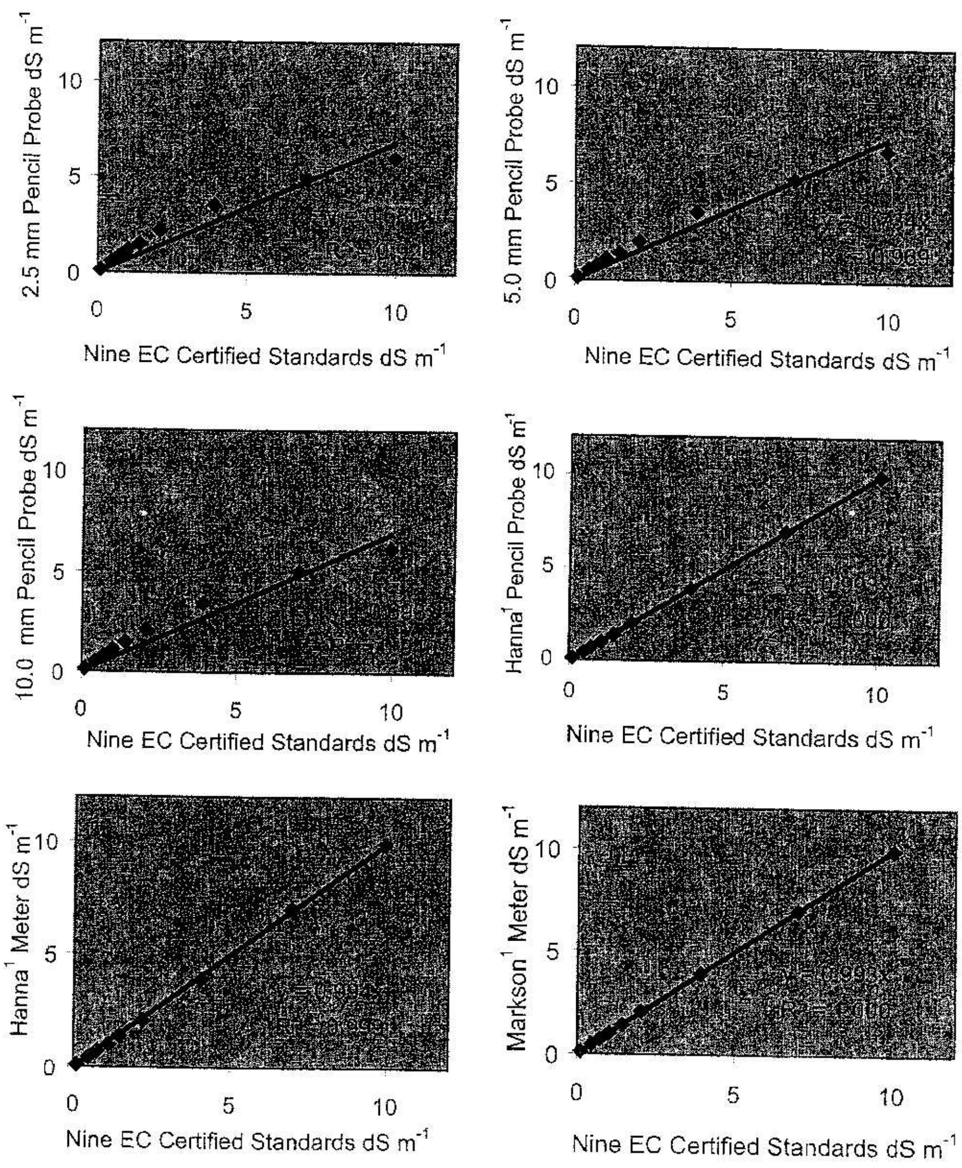


Figure 6. Use of EC certified standard solutions from 0.1 to 10 dS m^{-1} to compare performance of three pencil probes (2.5-, 5.0-, and 10.0-mm primary probes and 5.0-mm secondary probe) attached to a Hanna conductivity meter (DiST WP 4), a new Hanna "Prototype" pencil probe, a Hanna conductivity meter alone, and a Markson (Model 1062) conductivity meter standard.

conductivity and for qualitative screening measurements at EC values between 2.5 and 10 dS m^{-1}. However, as illustrated in Figure 6, the new prototype PP currently under development by Hanna Instruments is as accurate and precise as the Hanna (DiST WP 4) conductivity meter and the Markson (Model 1062) meter over the full range of conductivities tested (0–10 dS m^{-1}).

Applications

Alternate uses for the hand EC probes and PP include on-site assessments of EC and N fertility treatments as related to assessment of soil condition for microbially mediated processes such as greenhouse gas emissions and determining N levels in soil and plant tissue for in-season fertilizer applications.

As illustrated in Figure 7, field EC values measured in recently saturated soils using the BBII field probe were highly correlated ($r^2 = 0.997$) with standard laboratory EC measurements using 1 : 1 soil to water mixtures and were closely associated with fertilizer treatments, especially overfertilization.

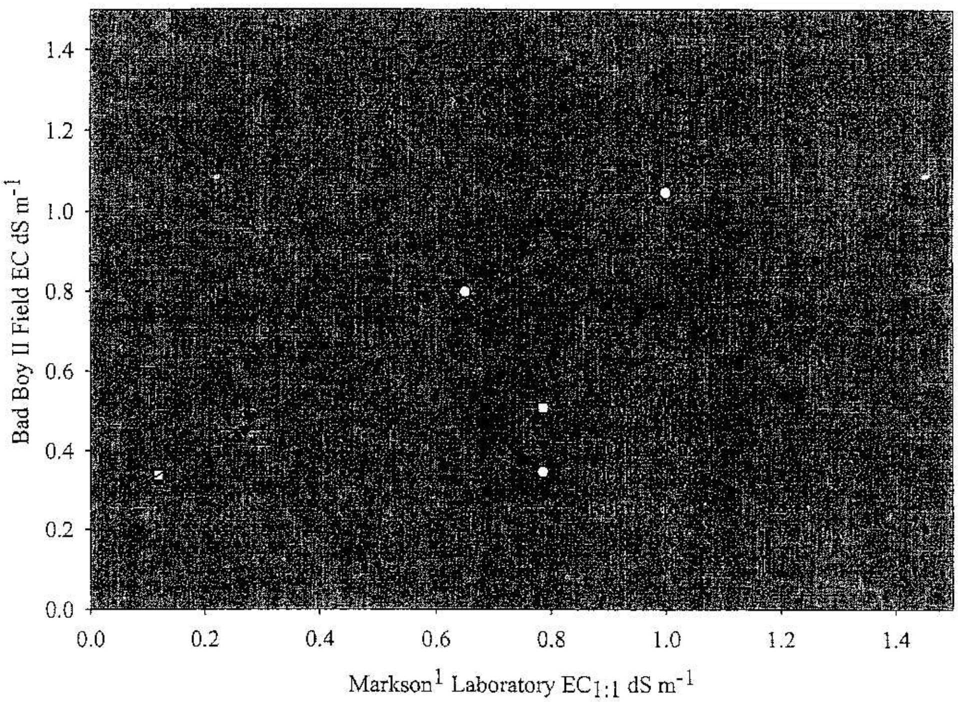


Figure 7. Comparison of mean EC values from in-field saturated soils using a Hanna conductivity meter attached to a BBII field probe compared with mean values from EC readings for soils transported to laboratory and measured as 1 : 1 soil water mixture using a Markson conductivity meter and probe. Plot points represent two sampling dates in a growing corn crop (July and August, 2001) within fertilizer rates of 0, 200, and 300 kg ha^{-1} and error bars illustrate the range of eight values (4 replications and 2 between row irrigation treatments) for an ecologically intensive study in Nebraska (after Amos et al. 2005).

This study also confirmed the utility of the field probe for in-field measurement of conductivity as an indicator of nitrous oxide emission from soil. In this particular field study, Amos et al. (2005) showed a highly significant correlation ($r^2 = 0.89$) between nitrous oxide flux from field cylinders and soil EC taken from the same field chambers after saturation with water. Adviento et al. (2004) have also effectively used the hand soil EC probes in the same experimental field to predict where increased nitrous oxide emissions could be expected and have demonstrated under controlled conditions in the laboratory that nitrous oxide emission from soil can increase when soil EC values exceed $0.8-1.0\,dS\,m^{-1}$. The field conductivity measurements were not only highly correlated with 1 : 1 EC measurements in the lab (Figure 6) but also provided a valuable estimation of nitrate N in the field after adjusting for nonnitrate EC background (Table 3). Eigenberg et al. (2000) demonstrated the utility of EC as an effective indicator of soil condition and N availability for irrigated corn (*Zea mays* L.) when field soil EC measurements are adjusted for nonnitrate EC background values.

The hand EC probes also proved useful for scouting soil fertilizer variability in the field. The BBIII probe (J. Schepers, personal communication 2003) worked well at locating starter-fertilizer bands in the field for proximity to seed placement and to determine the proper pattern for soil sampling for nitrate and ammonium analyses. The PP EC meter has also

Table 3. Utility of soil EC readings from in-field saturated soils using a field probe and laboratory EC readings using a Markson conductivity meter on 1 : 1 mixtures to estimate Nitrate-N as determined by standard laboratory procedures (after Amos et al. 2005)

Date sampled, fertilizer treatment	Soil EC readings ($dS\,m^{-1}$)[a]		Nitrate-N ($mg\,kg^{-1}$) Lab 1 : 1 extract	Nitrate estimated from EC minus background[b]	
	Field, Sat. BBII probe	Lab, 1 : 1 Markson		Field, Sat. BBII probe	Lab, 1 : 1 Markson
July 1, 2001					
Control	0.33 (29)	0.12 (18)	2.2 (61)	0.0	1.3
200 $kg\,N\,ha^{-1}$	0.45 (29)	0.27 (55)	16.4 (117)	15.4	20.5
300 $kg\,N\,ha^{-1}$	0.80 (38)	0.65 (54)	62.9 (76)	60.0	69.3
August 23, 2001					
Control	0.34 (15)	0.12 (42)	1.8 (19)	1.3	1.3
200 $kg\,N\,ha^{-1}$	0.48 (13)	0.28 (36)	12.1 (87)	19.7	20.3
300 $kg\,N\,ha^{-1}$	1.05 (34)	1.00 (62)	111.3 (75)	91.8	114.0

[a]Values in parentheses represent the % coefficient of variation for each mean ($n = 8$) of four field replications with two between locations, with and without irrigation tape.

[b]Backgroup EC values which represented nonnitrate salts as determined by soil nitrate analyses were $0.33\,dS\,m^{-1}$ for the Bad Boy II probe and $0.11\,dS\,m^{-1}$ for the laboratory 1:1 measurements.

proven useful in estimating differences in nitrate-N in N-sufficient and N-deficient corn plants. Stalk EC is not a reliable indicator of the nitrate-N content of a corn plant due to the multitude of ions contributing to conductivity in the cell sap. However, it appears that the difference in EC between a green and yellow (N-deficient) plant may be closely related to differences of nitrate-N as calculated from differences in EC (Table 4).

Soil EC can also serve as a rapid in-field estimate of nitrate-N in surface soils for use in the late spring or presidedress nitrate test (PSNT). As shown in Figure 8, soil EC was highly correlated ($r^2 = 0.77-0.83$) with NO_3-N in the surface 30 cm for 136 sites in IA and NE sampled by Gomes and Hillyer in 2003. Many of these sites were above the critical point of 25 ppm NO_3-N for corn after corn or the 16 ppm for corn after recent manure additions or after established alfalfa (Blackmer et al. 1993). It should be pointed out, however, that the PP was not used directly in the field but with 1 : 1 soil to water mixtures on composite soil samples from each site. It was interesting to note that most of these sites had soil pH values of 7 or below, and the average slope for the EC regression was 140, the theoretical value for the soil NO_3-N per unit of EC.

The EC PP also works very effectively after wet rainy periods to determine if available N has been lost from surface soils due to leaching or volatilization. A conductivity reading of 0.01 dS m^{-1} indicates less than 1.4 mg kg NO_3-N and a need for supplemental fertilizer.

CONCLUSIONS

Increased demand for rapid assessment of soil condition and plant nutrient status will facilitate the development of new technology and the improvement

Table 4. Use of the Hanna conductivity meter and pencil probe for estimating the available N status of corn at midseason

	Green corn plant receiving N fertilizer	Yellow corn plant without N fertilizer	Stalk EC or NO_3-N difference (green-yellow)	Estimated NO_3-N difference using EC[a]
EC of stalk	0.35 dS m^{-1}	0.15 dS m^{-1}	0.20 dS m^{-1}	28 mg L^{-1}
NO_3-N of sap	50 mg L^{-1}	20 mg L^{-1}	30 mg L^{-1}	—

The difference in stalk electrical conductivity between a green corn plant receiving N fertilizer and a yellow plant receiving no fertilizer was multiplied times 140 (ppm per dS m^{-1} EC) to estimate the difference in nitrate-N. This value was compared to the difference in plant sap NO_3-N analysis for the 4th internode of each plant where EC was measured.

[a]Estimated difference in NO_3-N content (mg L^{-1}) = EC difference (dS m^{-1}) X 140 mg N L^{-1}per dS m^{-1}.

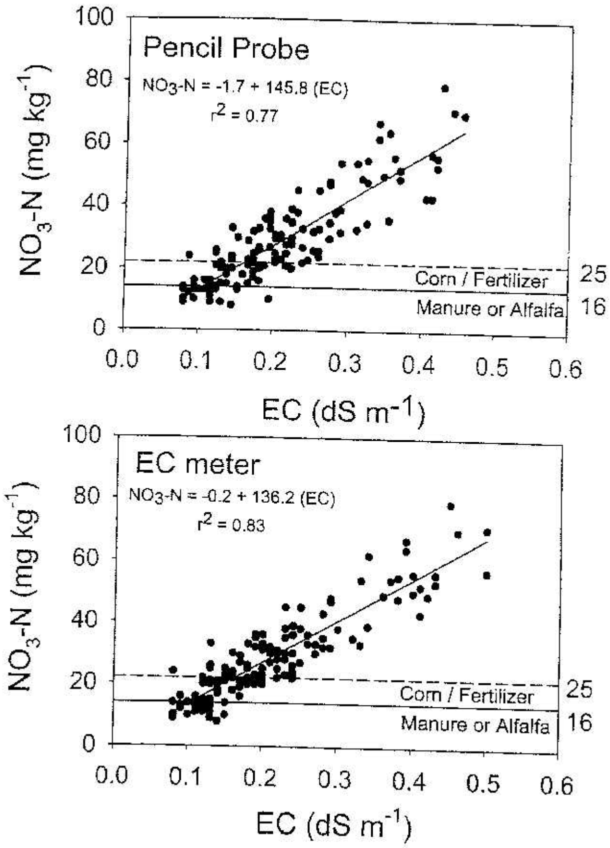


Figure 8. Relationship between EC of a 1 : 1 soil to water mixture (measured with a Hanna meter alone or with pencil probe) and soil nitrate-N values for 0- to 30-cm composite samples from 136 sites in SW Iowa and Nebraska. Samples taken in late spring for estimating sidedress N needs. Dashed line, critical limit for corn after corn; solid line, critical limit for corn receiving manure or corn after alfalfa.

of existing technology. Configuring a portable EC meter, as described in this manuscript with the PP, will provide scientists, consultants, and producers with a useful and economical tool for rapid qualitative insitu method for finding spatial variation of EC of soils and water sources in the field. The BBII, BBIII, and PP design, development, and evaluation have provided an easy to build and use, inexpensive, easy to use, and reliable alternative for EC measurements in the field and laboratory. The Hanna (DiST WP 4) conductivity meter, probe material, and assembly costs were less than $100.

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